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Some Studies on State and Disturbance Observer based Controller design for Uncertain Systems

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Some Studies on State and Disturbance Observer based Controller Design for Uncertain Systems

1) A brief resume of proposed problem

In real world control system applications, many state variables are not accessible and measurable. Even if measurable it becomes a costly affaire in number of applications. Popular solution for this is the Luenberger observer which estimates the unknown states of the system [1]. As the states get affected due to disturbances, this solution will not help in giving the accurate measurement of these states and will always generate steady state error. The control system performance is affected due to disturbances which widely exist in practical engineering in the form of actuator and sensor error, modelling error, system structure change, noise in measurement, internal vibrations, environmental disturbance and many more.

Industrial plants in real are highly nonlinear and time varying with high uncertainty. Not only the approximate mathematical model but various dynamics like, time delays, uncertainties, cross coupling, nonlinearities ,unknown disturbances, also needs to be taken into account while designing the control in industrial applications. It poses the challenge for control designers to design the control to tackle the systems that face the difficulties of unknown dynamics with unknown disturbances. Control strategies designed shall ensure the better performance of industrial processes by operating them within the limits of operating conditions and safety bounds. The unmeasurable states, unknown external disturbances and un-modelled dynamics are major concerns in many industrial applications. A lot of research is going on worldwide to deal with these issues in control systems.

To control the systems with unmeasurable states, different types of state observers are suggested in the literature. Different types of disturbance observers tackle the issues of unknown disturbances and to deal with uncertainties uncertainty and disturbance estimators are suggested [2].There are few common problems caused by sensors. First one is that the sensors are expensive. Use of sensors and its associated cabling significantly raise the total cost of control system. Reliability of control systems get reduced due to sensors and its wiring. Some signals are impractical to measure. The objects being measured may be inaccessible for such reasons as harsh environments and relative motion between the controller and the sensor. Sensors induce significant errors usually, such as stochastic noise, cyclical errors, and limited responsiveness. State observers replace the sensors needed in control system. These are actually the algorithms which combine sensed signals along with the other information of control system and produce observed signals. These signals obtained from observers can be less expensive with higher accuracy and reliability than sensed signals [3].

In practical engineering, disturbance widely exists in the form of modeling error, change of the system structure, measured noise, sensors and actuators error, internal vibration, external environment disturbance, and so on. Performance of the control system gets affected due to this. It also causes serious degradation in the system performance and even it may destroy the stability of the system. There are two types of methodologies focusing on the anti-disturbance control problem for systems with unknown disturbances. One is the disturbance attenuation method, such as nonlinear H_∞ control, sliding mode control, stochastic nonlinear control and so forth. The other is the disturbance rejection method including nonlinear output regulation theory and disturbance observer-based control (DOBC)[4]. DOBC is an idea in which the disturbances can be estimated by a disturbance observer and then it is compensated in the feed-forward channel immediately. DOBC has several features that give upper hand to it as compared to other anti-disturbance control approaches [4].Zhong and Rees has proposed a control strategy called Uncertainty and

Disturbance Estimator (UDE) which can be used to estimate the plant uncertainties as well as external disturbances without the knowledge of the bounds on the uncertainties. UDE is a control strategy that cancels model uncertainty and external disturbances, allowing for the straightforward control of complex nonlinear, time delayed systems with disturbances [5].

Considering all the merits and applications State observers, disturbance observers and UDE based control design, it is proposed to design control schemes for Single input Single Output (SISO) and Multi input multi output (MIMO) systems like two-link robotic manipulator, Flexible joint manipulator, Two-input–two-output (TITO) interactive processes like two tank, Quadruple tank systems, mismatched systems like magnetic levitation system etc. and simulate the results. To investigate how effective these control strategies are an experimentation and real time implementation for control of SISO and MIMO systems like flexible joint, two-link robotic manipulator, inverted Pendulum, interactive processes etc. can be considered.

2) Introduction to proposed research topic.

Control theory is often taught assuming the availability of near-perfect feedback signals. In fact, such an assumption is often invalid. Physical sensors have shortcomings that can degrade a control system. Observers work by combining knowledge of the plant, the power converter output, and the feedback device to extract a feedback signal that is superior to that which can be obtained by using a feedback device alone. Over the years, two classes of design methods for observers have emerged. One is concerned with state estimation based on a mathematical plant model; the other is concerned with disturbance estimation based on input output data. Plant Output Based Estimator (OBE), simply extracts information from the output of a plant or signal. Hence it is called an Output Based Estimator (OBE).If the plant model in the observer is accurate, inputs, and initial conditions are available then internal system states can be determined from inputs alone is called Plant Input Based Estimator (IBE). The Input Output based Observer (IOBO), popularly known as Luenberger observer is one which uses both the input and output data along with plant information to estimate the states and reduce noise and phase lag without the knowledge of initial conditions.

Estimating an unknown disturbance in addition to states is another idea of another category of estimators called disturbance estimators. The disturbance observer is different from state observer as it estimates external disturbances and observer model discrepancies that effectively appear in the plant model. Unknown Input Observer is another category of estimator which has the ability to estimate states and disturbances simultaneously. Perturbation observer can estimate the unmodeled plant variations along with external disturbances. Most of the estimators are made to handle slight perturbations for a modeled plant, however the Extended State Observer (ESO) removes the requirement of a modeled plant by rejecting un-modeled dynamics. The ESO uses a simple canonical form so the un-modeled dynamics appear at the disturbance estimation portion. Uncertainty and Disturbance Estimator (UDE) can be used to estimate the plant uncertainties as well as external disturbances without the knowledge of the bounds on the uncertainties.

Designing a controller is a challenging problem, in case of uncertain nonlinear multiple input multiple-output (MIMO) systems. It is because these systems are highly nonlinear and significant cross coupling exists between their control channels in open-loop dynamics and also by external disturbances and uncertainties in plant parameters. In such a situation, the conventional control schemes cannot give satisfactory control performance due to high coupling among the

control loops. The effect of input coupling, external disturbances, parameter variations and input nonlinearity as a lumped uncertainty which can be estimated by using techniques like UDE. This strategy makes control robust against coupling nature, external disturbances and parameter variations in MIMO system [6].

Trajectory tracking control of robotic manipulators with joint flexibility has received considerable attention owing to the complexity of the problem. For many manipulators, joint elasticity may arise from several sources, such as elasticity in gears, belts, tendons, bearings, hydraulic lines, etc. and limit the speed and the dynamic accuracy achievable by control algorithms designed assuming perfect rigidity at joints. In flexible joint robotic systems while designing the manipulator the problem of joint flexibility has received considerable attention as the major source of compliance. Therefore the joint flexibility must be taken into account in both modeling and control so as to achieve performance in tracking. Unwanted oscillations due to joint flexibility, imposes bandwidth limitations on all algorithm designs; based on rigid robots and may create stability problems for feedback controls that neglect joint flexibility. Control of flexible joint has been an important research topic and received considerable attention.

The Feedback Linearization (FL) is well known approach proposed for the trajectory tracking controller in flexible link manipulator. But FL control requires exact cancellation of nonlinearities and also needs the knowledge of all states to offer satisfactory performance [5]-[8]. In this situation, estimation of uncertainties along with the complete state vector is required. This requirement of obtaining the estimate of uncertainty as well as states in an integrated manner can be done with the help of Extended State Observer (ESO). The ESO estimates the effect of uncertainties, un-modeled dynamics and external disturbances acting on the system as an extended state of the original system. The ESO when integrated with FL can be used for trajectory tracking problem of flexible link manipulator where the effectiveness of ESO in estimation of states and uncertainties and obtaining satisfactory performance for the FL controller can be demonstrated.

Magnetic levitation system enables contactless motion of an object avoiding frictional drag. It is used in many applications such as high-speed magnetic levitation passenger trains, active magnetic bearings, artificial hearts, magnetic levitation, vibration isolation systems and high-speed turbines. Although it offers advantages, like high-speed, low maintenance and frictionless operation, its control is difficult because the system is open loop unstable and highly non-linear. Conventional Sliding mode control (SMC) has some limitations that the bounds of uncertainties and the disturbances should be known, discontinuous control may cause excessive wear of the actuator and it requires a full state vector to be available for measurement for its implementation. These limitations can be overcome if cascaded DO-based SMC is designed for electrical system and electromechanical loop is controlled with a state and disturbance observer (SDO)-based SMC of the magnetic levitation system [7].

3) Review of literature and development in the relevant subject

The design and development of control strategies like state and disturbance observers based control of uncertain systems in presence of disturbance is reviewed in the following context

1. State observers, disturbance estimators, compensators and controllers
2. State and Disturbance observer based control design
3. Applications of these techniques for nonlinear uncertain systems
4. Recent work on state and disturbance estimator based control

State observers, also known as estimators, play a central role in modern control theory Since 1970s, many effective disturbance estimation techniques have been developed, such as Unknown Input Observer (UIO), where the disturbance is treated as an augmented state of the plant. The state observer is designed to estimate both the original states and the augmented one. The disturbance is then rejected by using its estimated value obtained by the observer. Another class of disturbance estimators is known as the Disturbance Observer (DO), where the disturbance is estimated by using the inverse of the nominal transfer function of the plant. In addition to the UIO and the DO, there are also scattered reports of different variations, such as the adaptive robust controller, the adaptive inverse controller, and model-based disturbance attenuation method. Some researchers proposed the Perturbation Observer (PO) to estimate the disturbances in a discrete state space form. Another class of such disturbance estimators are Equivalent Input Disturbance (EID) based estimator and Extended State Observer (ESO). What sets the ESO apart from the UIO and the DO is that it is conceived to estimate not only external disturbances but also plant dynamics. Among the disturbance estimators, the ESO requires the least amount of plant information [2].

Sliding mode control has been proven to be an effective technique to control systems which are affected by parametric uncertainties, inherent nonlinearities, and external unmeasurable disturbances. It can make their performance insensitive to parametric variations and external disturbances, when the system is in sliding mode. However, this property of conventional SMC is observed only when the uncertainties and disturbances satisfy the so-called matching conditions. With the severe sensitivity problem of the optimal control theory in engineering applications, robust control was emerged to deal with plant uncertainties and external disturbances in the beginning of 1970s. Several robust control techniques since then have been proposed in the literature. Among them, DO is one of the most popular robust control tools due to its simplicity, flexibility and efficacy. In DO-based robust control, internal and external disturbances are estimated by using identified dynamics and measurable states of plants, and the robustness of systems is simply achieved by feed backing the estimations of disturbances. In the last four decades, this intuitive robust control technique has been experimentally verified in many different engineering applications, such as in robotics, mechatronics, automotive and power electronics.

Several conventional control approaches like high gain control, adaptive control, sliding mode control etc. are used in order to handle the systems affected by plant uncertainties, unmeasurable and unpredictable external disturbances. Many of these needs that all state vector is measurable. In many systems it is highly impossible to measure all states of the systems. State observer concept can be used in such circumstances. The concept of ESO, Do and UDE can be used to control the systems with uncertainties and unpredictable external disturbances. It has shown as a powerful paradigm to produce satisfactory performance. Various disturbance estimators like Disturbance Observer(DO), Unknown Input Observer (UIO), Perturbation Observer (POB), Extended State Observer (ESO), Uncertainty and Disturbance Estimator(UDE)[1][2]. Estimators are reviewed in terms of applicable dynamic structure of plant.

Sanjay E. Talole, Jayawant P. Kolhe, and Srivijay B. Phadke, used FL-based controller for the trajectory tracking problem of flexible-joint robotic system. To address the issues of uncertainties and the estimation of state, an ESO is designed and integrated with the FL controller. The proposed controller robustifies FL-based controllers and makes them implementable by providing an estimate of states. This is accomplished by designing an ESO that provides estimates of uncertainty and states simultaneously and integrating it with the FL controller. The design requires measurement of position on the link side only, unlike many schemes that need more measurements. As the effect of uncertainties is compensated by estimating the same, the design does not need knowledge of any characteristic such as the bound of the uncertainties. The design is far less model dependent in comparison with many control schemes that appear in literature [12].

The conventional SMC shows insensitivity to matched uncertainties and disturbances. While for a large class of systems, the uncertainties and disturbances are matched, there are many practical systems for which this is not true .Divyesh Ginoya, P. D. Shendge and S. B. Phadke have proposed a ESO based SMC controller to handle a larger class of mismatched uncertainties by extending the disturbance observer and modifying and generalizing the sliding surface [30].

A A Godbole, T R Libin, and S E Talole ,in their work a new design based on the extended state observer (ESO) technique for the pitch autopilot of a tail-controlled, skid-to-turn missile is proposed. The pitch-plane dynamics with the angle of attack as output is significantly uncertain. The ESO simultaneously estimates the state and the uncertainty. The estimated uncertainty is used to robustify the input–output– linearization-based controller designed for the nominal system. Closed-loop stability of the observer–controller combination is proved. The notable feature of the proposed design is that it neither requires accurate plant model nor any information about the uncertainty. The effectiveness of the ESO in estimation of the uncertainties and states and in meeting the specified tracking performance in the presence of significant uncertainties is illustrated by simulation.

The ESO, GESO, DO, EDO and UDE has been applied to many linear and nonlinear systems. Several applications of the based on these controllers have also been reported in the literature. The nonlinear systems are linearized using a feedback linearization (FL) and the observer based control law is made implementable using ESO, is proposed for the trajectory tracking control of a flexible joint robotic system in [9,10]. Shendge and Patre applied a SMC-based UDE controller to a linearized load frequency control, concluding that the proposed methodology offers excellent tracking capabilities for changing all parameter from 50% to 98% from their nominal values[11]. Dadekar et al. proposed full-order model following sliding mode control based on UDE technique and implemented on MIMO system. The effectiveness of control scheme is demonstrated through numerical simulation of two-link manipulator [14]. 32. Divyesh , Ginoya, Chandrashekhar M Gutte, PD Shendge and SB Phadkehave proposed a cascaded sliding mode control for magnetic levitation systems usually comprised of an electrical loop and an electromechanical loop. A disturbance-observer-based sliding mode controller is designed for the electrical loop while a state-and-disturbance-observer-based sliding mode controller is designed for the electromechanical loop [32].

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4) Objectives of the research and proposed hypothesis.

1. Study of various systems with uncertainties and un modelled dynamics
2. Study of various state observer techniques
3. Study of various Disturbance estimation and compensation techniques.
4. Study of uncertainty and disturbance estimation techniques and control Laws.
5. Design of State / disturbance observer based control laws for SISO and MIMO systems like DC servomotor, Two-link robotic manipulator, coupled tank system, Flexible joint manipulator, Interacting processes, CSTR etc.
6. Design of State / disturbance observer based control schemes for nonlinear systems with mismatched uncertainties and disturbances.
7. Numerical simulation and Experimental validation
8. Investigation and real time implementation.

5) Methodology to be used and adopted

The following methodology is used to meet the objectives and according the work is divided into distinct phases:

- Study and design of state estimation methods like state observer, extended state observer (ESO)and Generalized Extended State observer(GESO) to measure the unmeasurable states and also counter the effects of external unpredictable disturbances in SISO and MIMO system.
- Study and design disturbance observer (DO), Extended Disturbance Observer (EDO) and different UDE techniques in order to deal with Effects of uncertainties and disturbances. These strategies shall be used in combination with SMC, Backstepping, Multi time scale feedback control or similar strategy shall be used to fulfill the objectives.
- Control schemes shall be validated by simulation in Matlab /Simulink environment as well as by conducting experiments on a laboratory setup.
- Comparative study, stability analysis and performance evaluation.

6) Importance of the study

Practical systems like various chemical processes, nuclear reactors, electrical, hydraulic and mechanical systems are generally modelled as nonlinear systems with time delay. Practically in many control applications the states are unmeasurable due to adverse environment. Disturbances and uncertainties widely exist in all industrial systems and bring adverse effects on performance and stability of control systems. In such circumstances it is economically desirable to operate the chemical processes, robotic systems, nuclear power reactor etc. at close to the desired operating levels or designed power levels. Many benchmark controllers like PID, SMC etc. are used traditionally to control the systems. But if disturbances and uncertainties in the parameters increases, the performance of PID controller becomes poorer. It indicates that the PID controllers are unable to deal with such issues like unmatched disturbances, uncertainty and, frequent load changes. Robust strategy like SMC gives an acceptable control performance but at the cost of chattering phenomenon in the control signal with the limitation that the upper bound on uncertainty must be known.

In this context to deal with effect model uncertainty and disturbance, it is required to estimate the disturbance or its influence from measurable variables and then, generate control action based on the estimate to compensate it. There are many disturbance estimation and

compensation techniques in literature. The objective of this study is to propose most simple and generalized control design strategy to counter the dynamics based on estimation. A simpler observer and compensation technique are used to deal with the mentioned dynamics in the various applications discussed.

The basic idea of Disturbance Observer based control (DOBC) is that the disturbances can be estimated by a disturbance observer and then it is compensated in the feed-forward channel immediately. Compared with other anti-disturbance control approaches, DOBC has several features. One feature of DOBC is that it can provide a stability analysis and synthesis approach for systems with disturbances. The second one is its simple structure, and it is easy to be adjusted online; the third one is that DOBC can be integrated with other control Strategies, which is considered as a composite hierarchical anti-disturbance control method.

Uncertainty and disturbance estimation is another control strategy that cancels model uncertainty and external disturbances, allowing for the straightforward control of complex nonlinear, time delayed systems subject to disturbances. The strategy has been applied successfully in the extension of control strategies initially designed for systems without disturbances (input output linearization, feedback linearization, sliding mode control). The main idea behind the controller is that a filter of appropriate bandwidth can estimate an unknown signal accurately enough, so the estimation can be utilized in the control design to cancel system uncertainties and external disturbances. The proposed work will add new methodology and characteristics of observer based control which can be applied to linear systems with fast varying disturbances, nonlinear systems like CSTR and multi-variable systems which has interactions, coupling effects, robotic manipulators to obtain desired performance. The control design will be validated by simulation in Matlab/Simulink environment as well as by conducting experiments on a laboratory setup.

7) Proposed work plan- with a tentative chapter scheme

- Chapter 1: Introduction and Literature Survey
- Chapter 2: State and Disturbance observer based control law
- Chapter 3: State /Disturbance based control law for SISO and MIMO systems
- Chapter 4: Investigation of State/Disturbance observer based control strategies for linear and nonlinear benchmark models of uncertain systems
- Chapter 5: Investigation of State /Disturbance observer based control strategies for Process control applications
- Chapter 6: Investigation of State /Disturbance based control strategies for Mechanical/Robotic mismatched Systems
- Chapter 7: Comparative study and analysis
- Chapter 8: Conclusion

8) Year wise plan of work and targets to be achieved

Sr. No.	Year 1	Year 2	Year 3
1	Literature Survey of State/Disturbance observer based control strategies (Luenberger observer, ESO, GESO, DO,EDO, and UDE) applied for uncertain systems, study of key parameters in the design of these estimators, stability issue, and applications etc.	Study and design of State observer/ESO/ GESO/DO/EDO /UDE based control strategies for linear, nonlinear benchmark models and systems eg. Two tank system Inverted Pendulum	Study and design of UDE based control strategies for linear and nonlinear models like Robotic systems. e.g. Flexible link manipulator, Magnetic levitation system etc.
2	Study and design of State/Disturbance observer based control law for the applications given in the literature	Design and Investigation of State/Disturbance observer based control strategies for process control applications like coupled tank , robotic manipulator etc.	Comparative study and analysis of proposed control strategies on the basis of accuracy, robustness and effectiveness
3	Using MATLAB Simulink, implement the different control laws based on state and disturbance estimation	Experimentation and real time implementation of State/ Disturbance observer based control strategies.	Preparation of Report

9) Expected outcome

1. Simulation of different State/Disturbance observer based control strategies in Literature.
2. Design of State/Disturbance observer based control strategies for linear and nonlinear uncertain system and benchmark models.
3. Investigation of State/Disturbance observer based control strategies for process control applications like CSTR, Two tank system , Quadruple tank systems.
4. Investigation of State/Disturbance observer based control strategies for linear and nonlinear model of Robotic systems. Magnetic levitation system etc.
5. Performance comparison of the proposed control strategy in terms of robustness and effectiveness

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